

A search for

Stellar-Mass Black Holes In the Solar Neighborhood

using the Sloan Early Data Release
(with Jim Chisholm & Scott Dodelson)

Pylos, 29 April 2002

Rocky Kolb

Fermilab/Chicago/CERN

Holes in 'da 'hood!

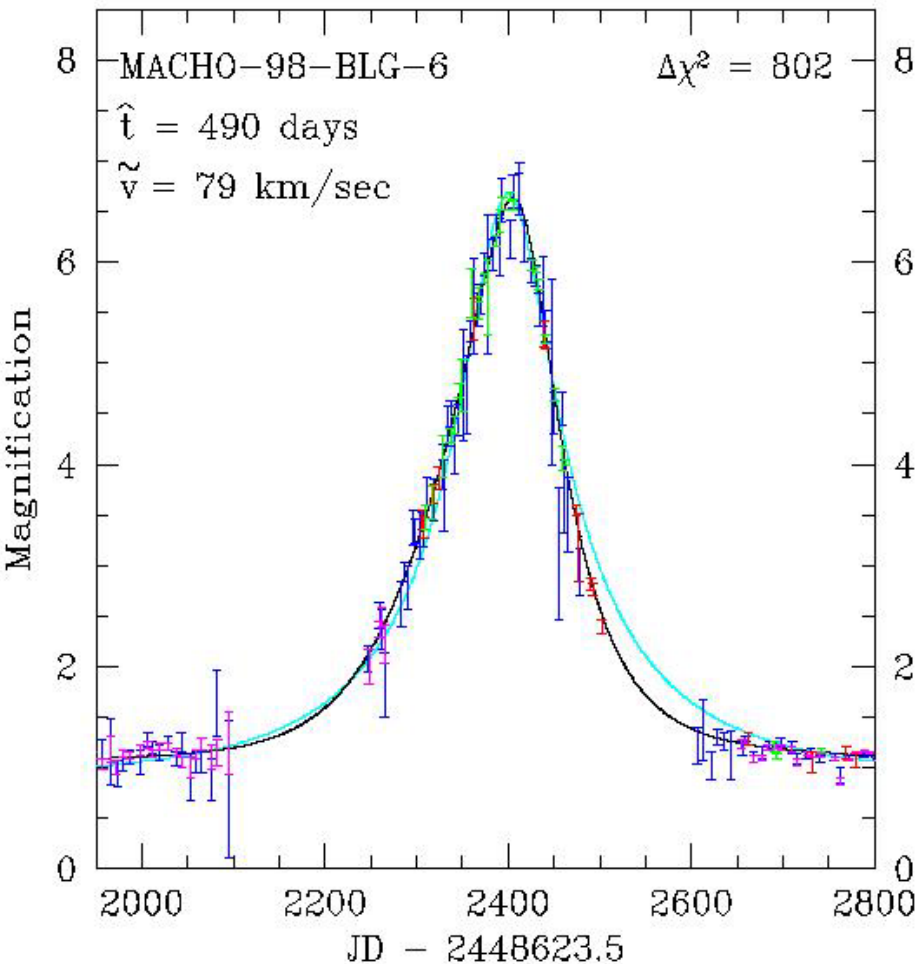
- How near could a $1 M_{\odot}$ black hole be and have escaped detection? * $M_v \geq 16.5$
- Black holes are interesting astronomical objects
- Possible endpoints of stellar evolution
- Unique laboratory to study “strong gravity” (end of time)
- Remnant black holes provide information about
 - stellar evolution
 - galaxy formation
 - dark matter

* Black holes are everywhere you can't prove they are not.
-- Zel'dovich

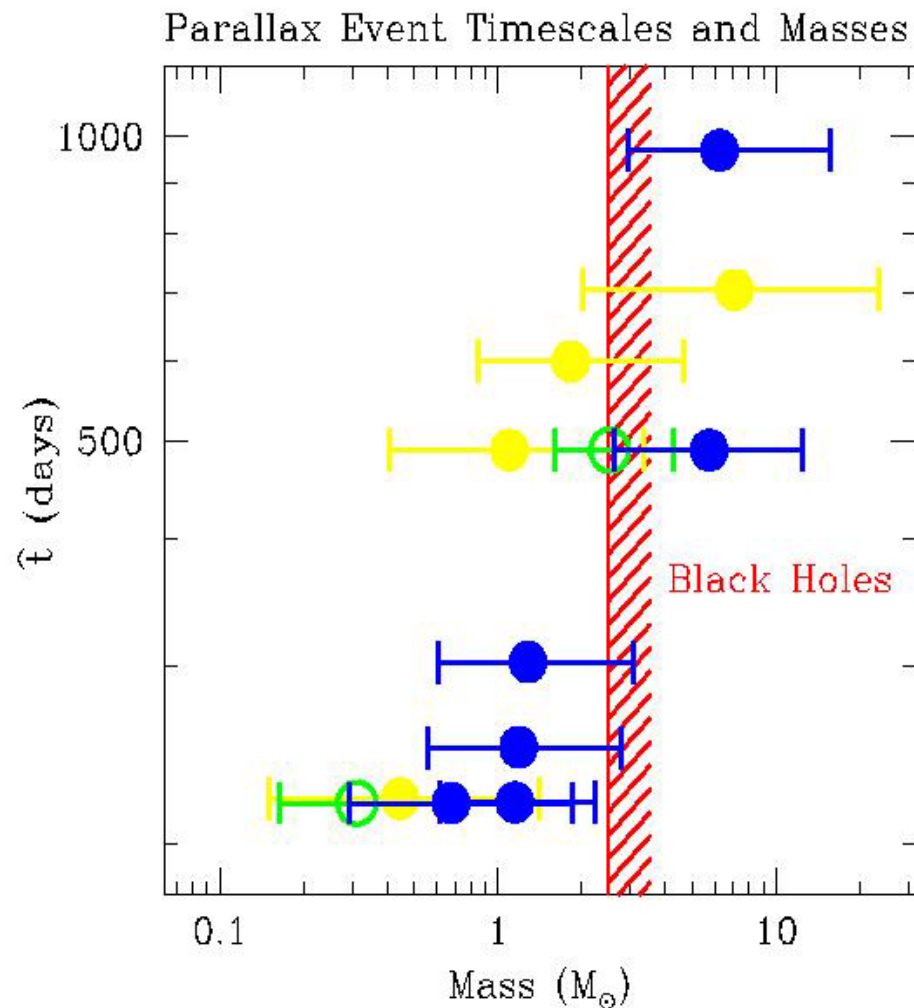
Holes in 'da 'hood!

- We are interested in “stellar mass” black holes
 $M = 3 \text{ to } 100 M_{\odot}$
- About 10^9 neutron stars in the galaxy
- Black holes detected via microlensing?
(Mao et al. 2001, Bennett et al. 2001)
 10^8 to 10^9 in the galaxy?
- Black holes are really dark
 - Hawking temperature for solar-mass hole
is pitifully small: $T_H = 10^{-10} \text{ eV}$
 - Look for the hole's effects on the environment

Microlensing *black-hole* *candidates*



Bennett et al.
(also Mao et al.)



Holes in 'da 'hood!

- We are interested in “stellar mass” black holes
 $M = 3 \text{ to } 100 M_{\odot}$
- About 10^9 neutron stars in the galaxy
- Black holes detected via microlensing?
(Mao et al. 2001, Bennett et al. 2001)
 10^8 to 10^9 in the galaxy?
- Black holes are really dark
 - Hawking temperature for solar-mass hole
is pitifully small: $T_H = 10^{-10} \text{ eV}$
 - Look for the hole's effects on the environment

Accretion powers the luminosity

$$L = \varepsilon \dot{M}$$

\dot{M} = accretion rate

Useful benchmark is Eddington luminosity where
radiation pressure = gravitational pressure

$$L_{\text{Eddington}} = \frac{4\pi G M m_p}{\sigma_T} = 1.3 \times 10^{38} \left(\frac{M}{M_{\odot}} \right) \text{ erg s}^{-1}$$

the program: $\left\{ \begin{array}{l} 1. \text{ Calculate } \dot{M} \\ 2. \text{ Calculate } \varepsilon \end{array} \right.$
[actually want $\varepsilon(\nu)$]

Spherical accretion

Object with mass M
moving with velocity v
through a cold, collisionless gas of density ρ

- geometrical:

$$\dot{M} = \pi R_{BH}^2 \rho v$$

$$R_{BH} = \text{hole radius} \\ = 2GM$$

- gravitational:

$$\dot{M} = \pi R_A^2 \rho v$$

$$R_A = \text{accretion radius} \\ = \frac{2GM}{v^2}$$

collisionless \longrightarrow pressureless

\downarrow
supersonic flow $v \gg v_s = 17 \text{ km s}^{-1}$

$R_A \ll$ mean free path
between collisions

Spherical accretion

Object with mass M
moving with velocity v
through a cold, collisional gas of density ρ

- Bondi accretion:

$$\dot{M} = \pi R_B^2 \rho v_s$$

R_B = Bondi radius

$$= \frac{2GM}{v_s^2}$$

collisional \longrightarrow pressure
 \downarrow
subsonic flow $v \ll v_s = 17 \text{ km s}^{-1}$

- interpolation:

$$\dot{M} = 4\pi G^2 M^2 \rho \frac{\sqrt{v^2 + v_s^2}}{(v^2 + v_s^2)^2}$$

Spherical accretion

In our neighborhood

$$v_s = 17 \text{ km s}^{-1}$$

$v =$ gaussian with $\sigma = 40 \text{ km s}^{-1}$ (X-ray binary population)

$$\rho = 10^{-24} \text{ g cm}^{-3}$$

$$\dot{M} = 4 \times 10^{-17} \left(\frac{M}{M_{\odot}} \right)^2 M_{\odot} \text{ yr}^{-1} = 2 \times 10^{30} \left(\frac{M}{M_{\odot}} \right)^2 \text{ erg s}^{-1}$$

$$L = 6 \times 10^{-4} \left(\frac{M}{M_{\odot}} \right)^2 \varepsilon L_{\odot}$$

Spectrum

Shvartsman (71), Zel'dovich, Novikov, Thorne, Shapiro...
Ipser & Price

- Accretion of ISM
- Bremsstrahlung and thermal emission weak, but....
- Magnetic fields present and frozen in the ISM
- Magnetic fields drawn in to hole and compressed
(as large as 10 tesla!)
- Emission through synchrotron radiation
- Efficiencies as high as $10^{-2} \dot{M}$ ($\varepsilon \propto \dot{M}$)

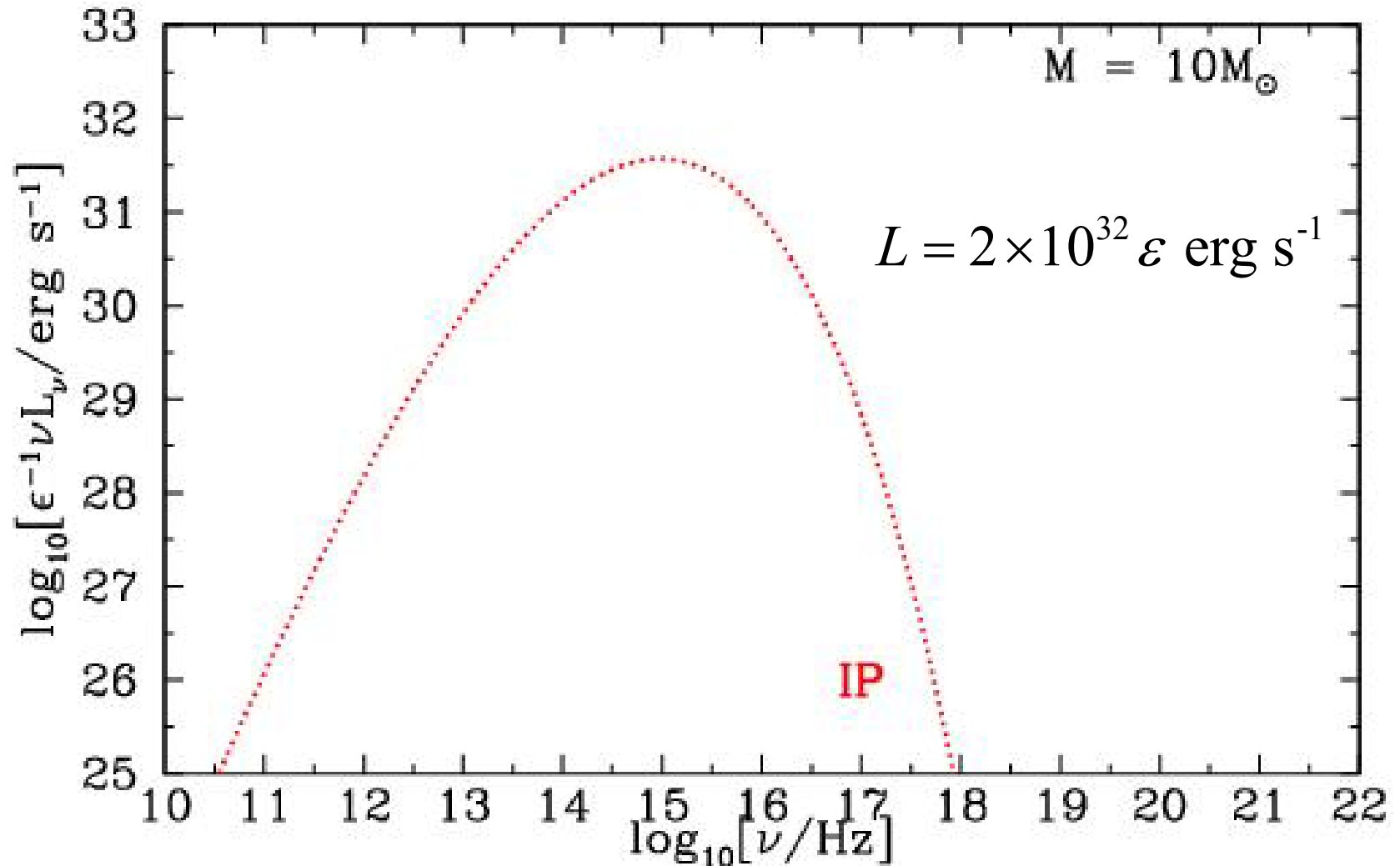
$$L = 6 \times 10^{-4} \left(\frac{M}{M_{\odot}} \right)^2 \varepsilon L_{\odot} = 6 \times 10^{-4} L_{\odot} \quad \text{for } M = 10 M_{\odot}$$

$$M_{bol} = 13 \quad (m_{bol} = 23^{\text{rd}} \text{ at 1 kpc})$$

Model spectral energy distributions:

$$L = \int \frac{d\nu}{\nu} \nu L_\nu$$

$\nu L_\nu =$ spectral energy distribution
(contribution per decade)



Spectrum

Igumenshchev & Narayan (2001)

- claim flow is convectively unstable
3-D magnetohydrodynamics \longrightarrow CDBF
- drastically decreased accretion rate (about 10^{-9} !)
- ... but accretion probably not be spherical!

Spectrum

inhomogeneties in ISM or magnetic field

—————→ *form optically thin disk*

ADAF (advection dominated accretion flow) model

- two-temperature structure
- lower luminosity
- synchrotron dominates near optical $\nu_{\text{peak}} \propto M^{-3/8}$
- broadband emission (radio to X ray)

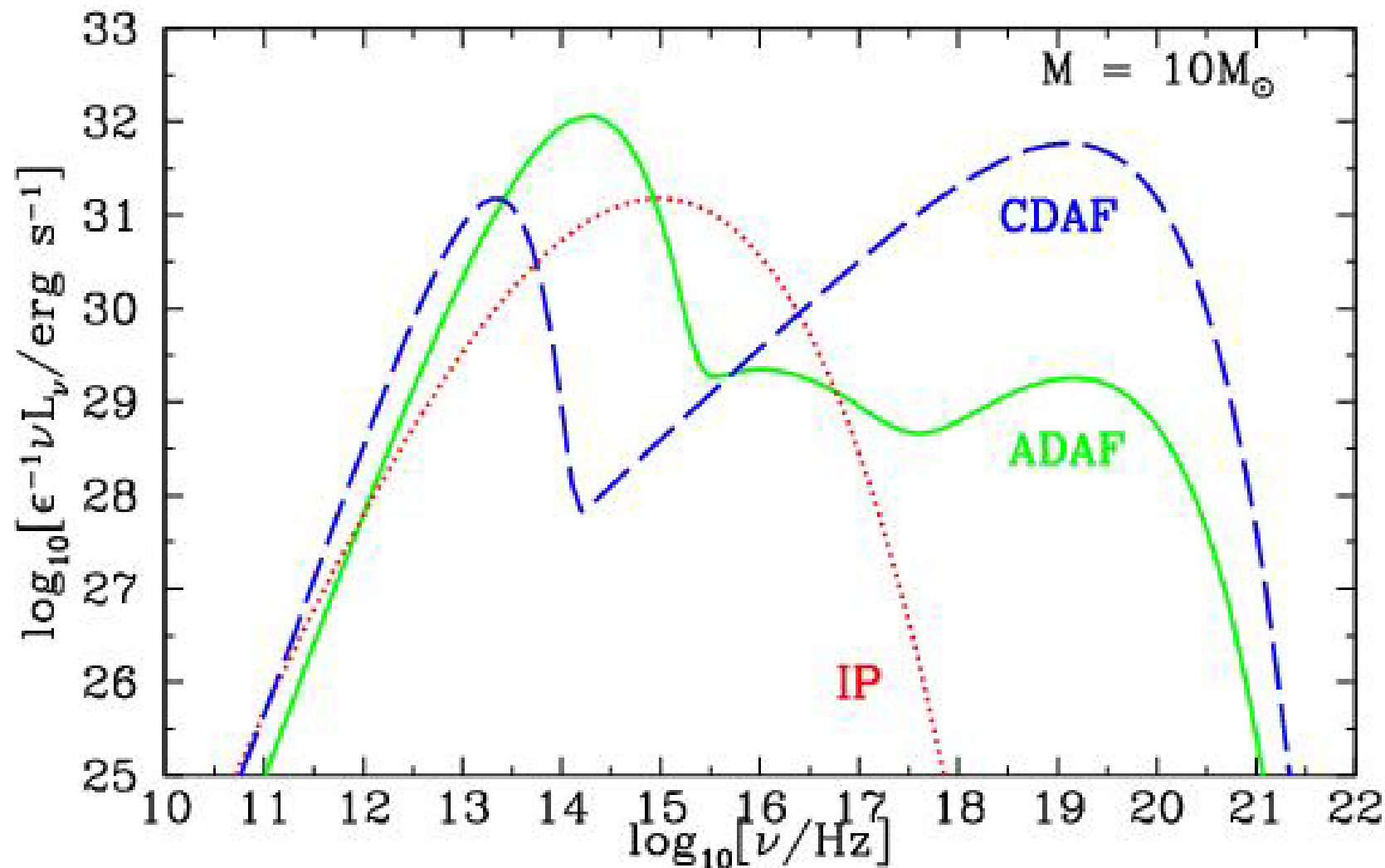
CDAF (convection dominated accretion flow) model

- somewhat lower luminosity
- synchrotron dominates near optical
- even more pronounced X-ray peak

Model spectral energy distributions:

$$L = \int \frac{d\nu}{\nu} \nu L_\nu$$

$\nu L_\nu =$ spectral energy distribution
(contribution per decade)



Model spectral energy distributions:

Luminosity & spectrum uncertain, but

Common observational signatures:

- **synchrotron radiation in optical
broken power law**

$$\nu L_\nu \propto \nu^3 \quad (\nu \ll \nu_{\text{peak}})$$

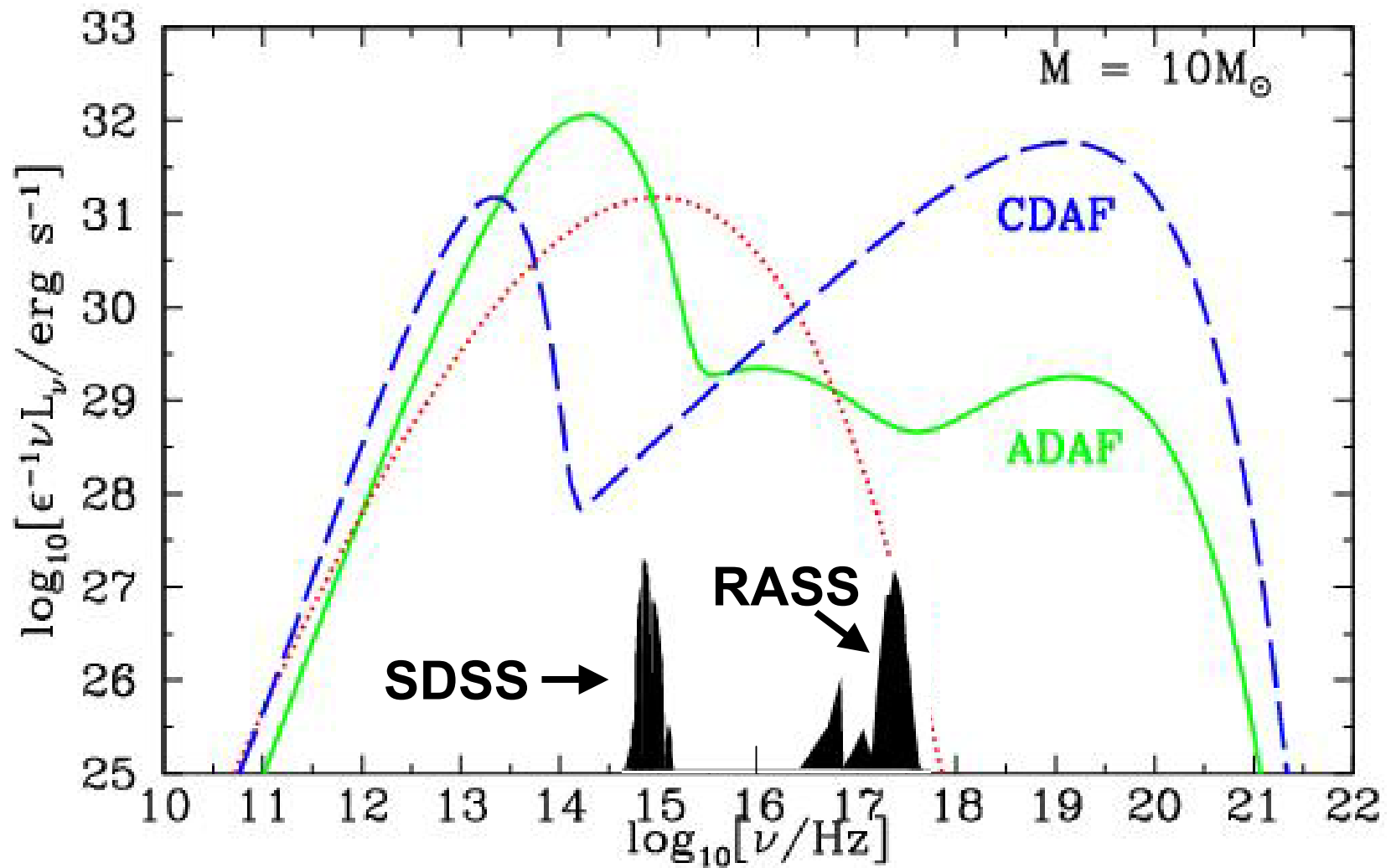
$$\nu L_\nu \propto \nu^{-2} \quad (\nu \gg \nu_{\text{peak}})$$

- **X Rays**

Model spectral energy distributions:

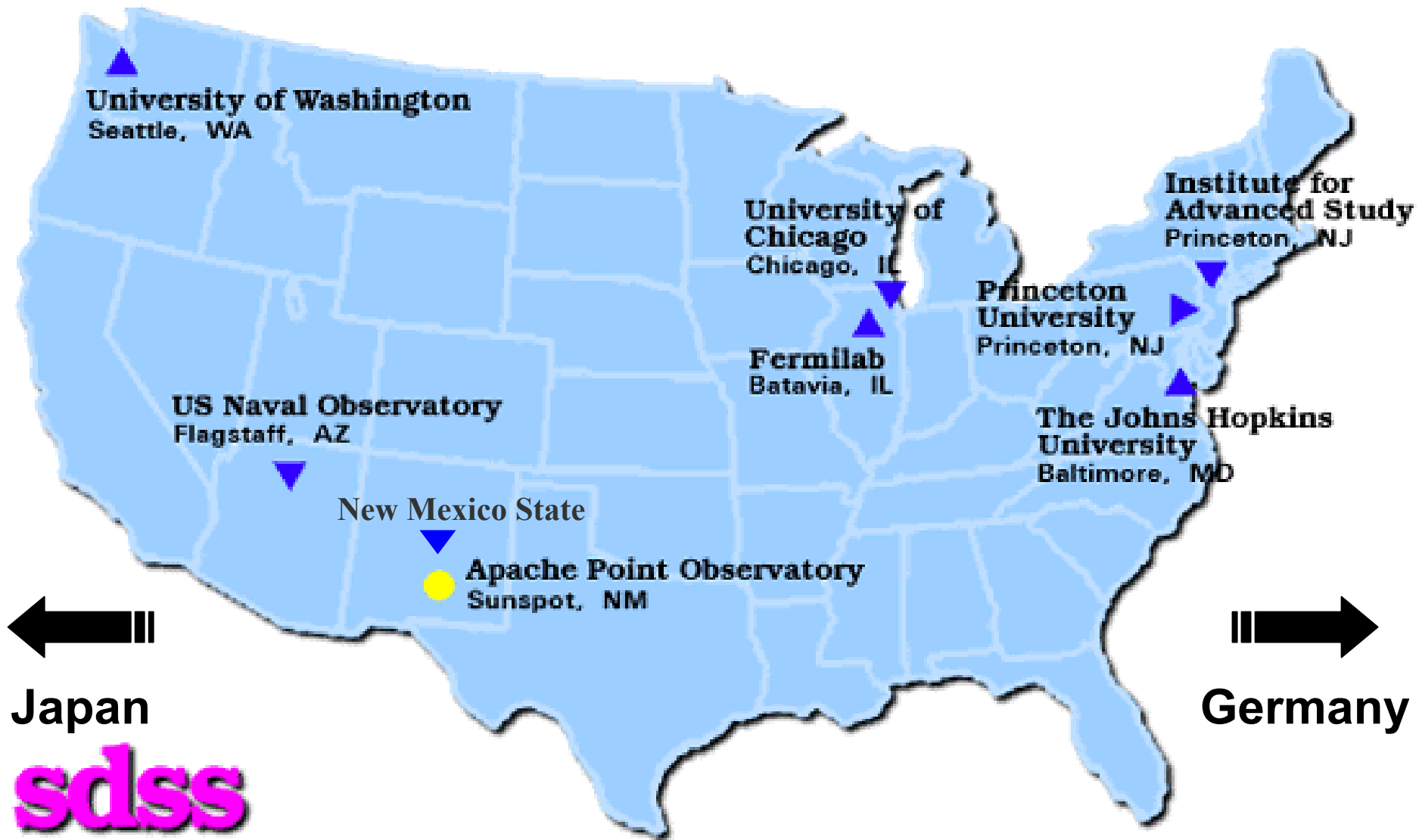
$$L = \int \frac{d\nu}{\nu} \nu L_\nu$$

$\nu L_\nu =$ spectral energy distribution
(contribution per decade)



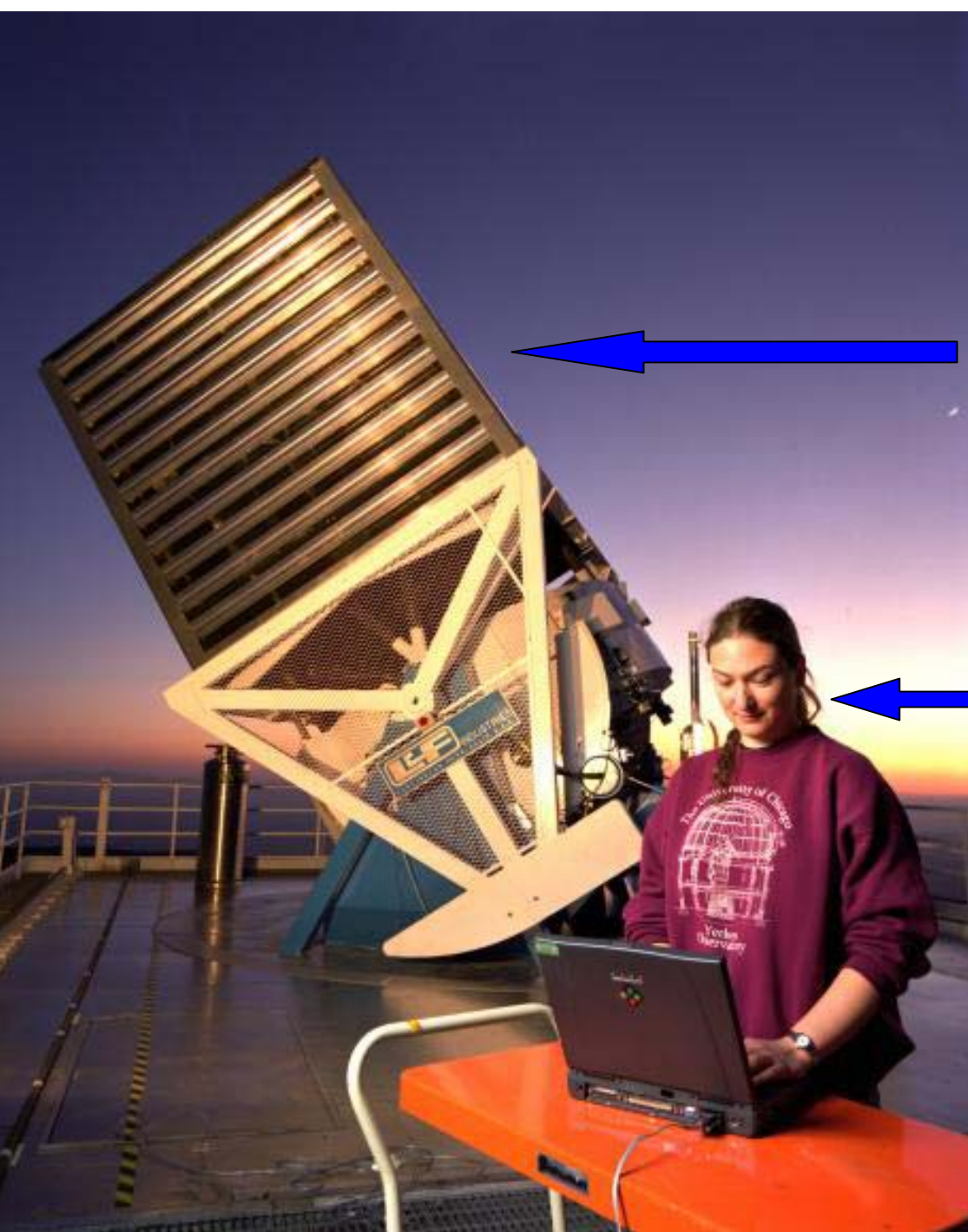
Construct a 2.5m telescope & instruments to

1. image the sky to 23rd mag in 5 colors (10^9 objects)
2. take the spectra of 10^6 objects (mostly extragalactic)



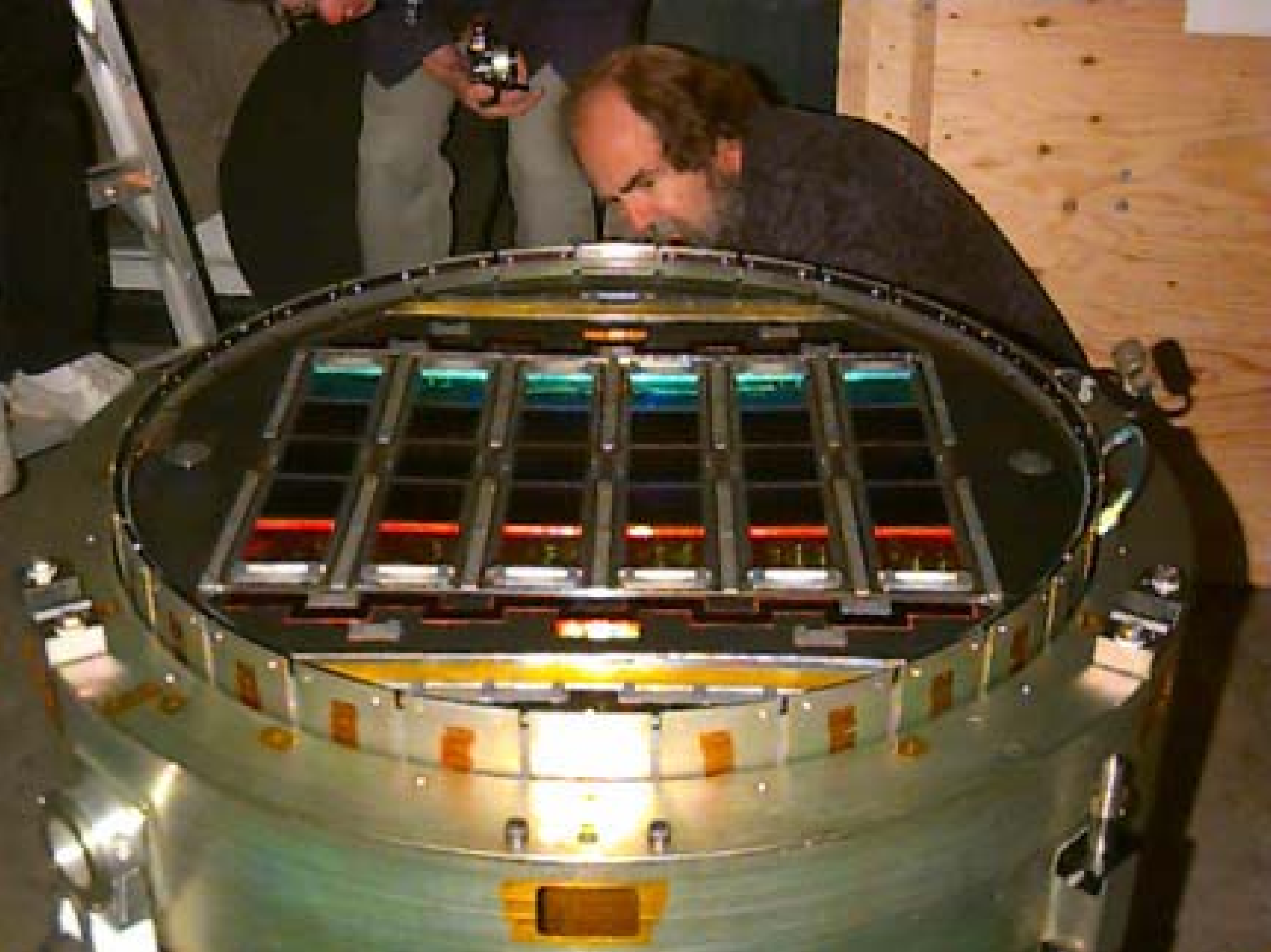


SDSS

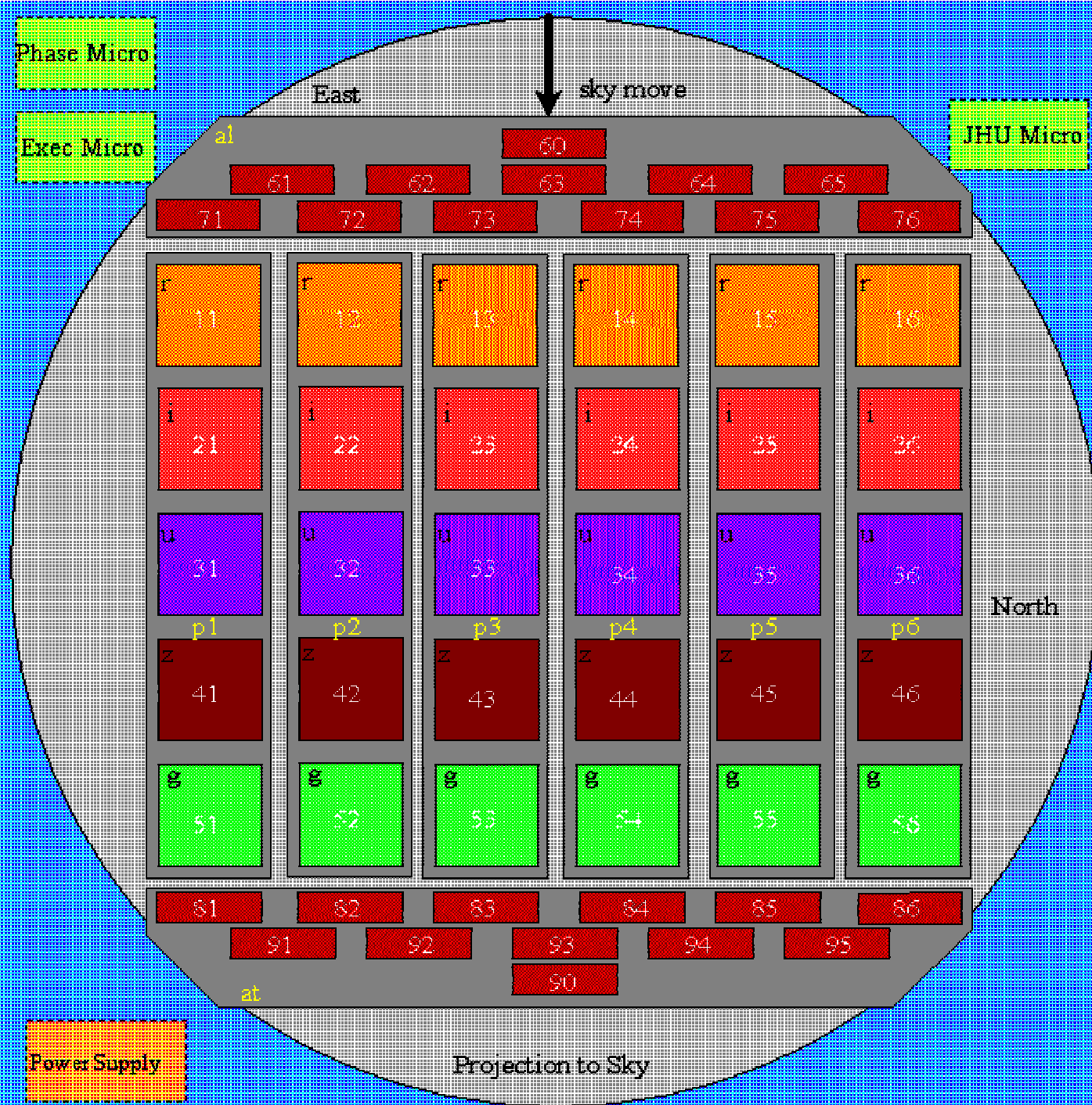


2.5 m telescope

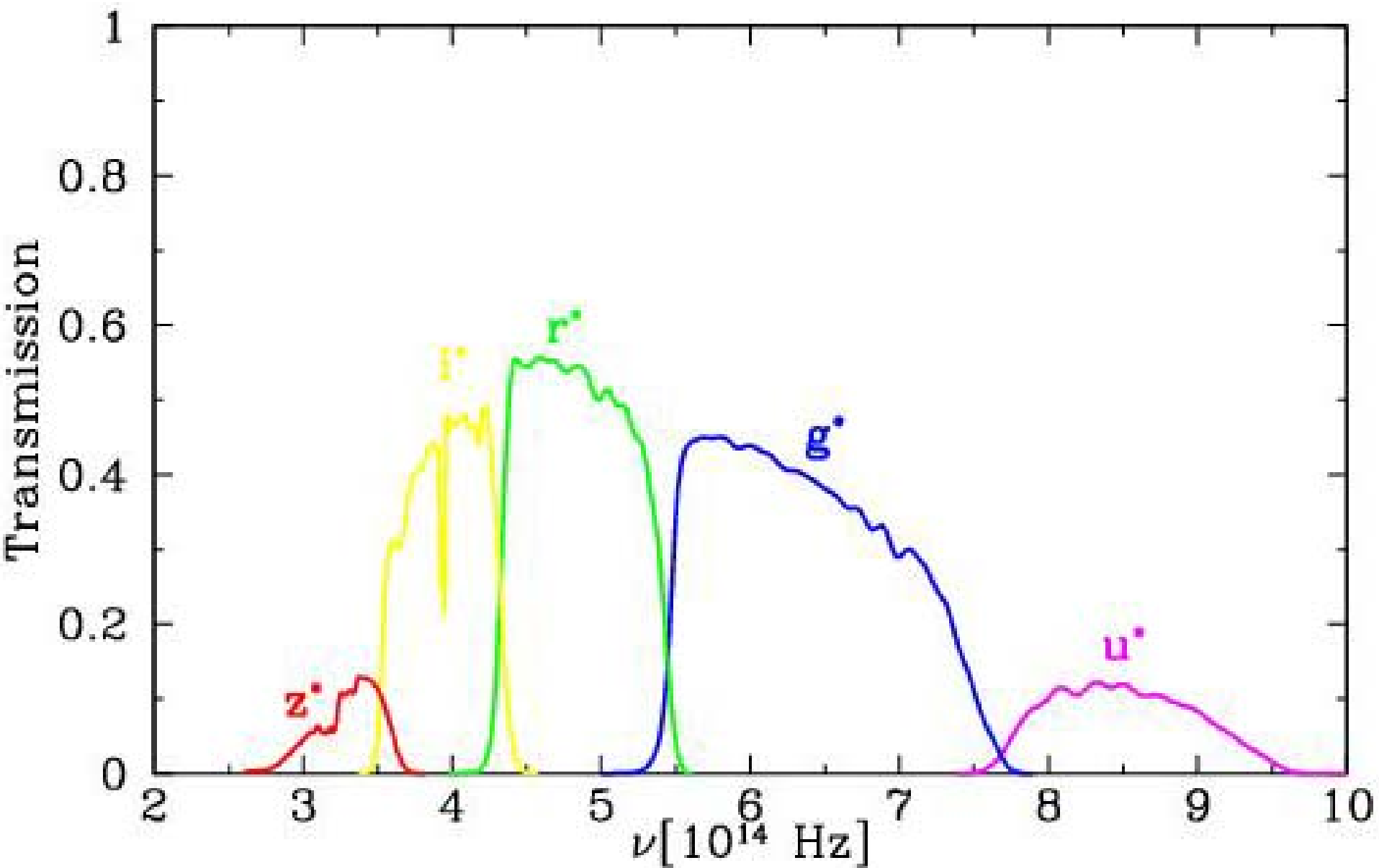
data acquisition system



SDSS camera



SDSS colors



Detection by SDSS

Assume

1) broken power-law spectral energy distribution:

$$[\nu L_\nu] = [\nu L_\nu]_{\text{peak}} \begin{cases} \left(\nu / \nu_{\text{peak}} \right)^3 & \nu \leq \nu_{\text{peak}} \\ \left(\nu / \nu_{\text{peak}} \right)^{-2} & \nu \geq \nu_{\text{peak}} \end{cases}$$

2) scaling as in ADAF model: (Manmoto, Mineshige & Kusunose;
Fujita, Inoue, Nakamura, Manmoto & Nakamura)

$$[\nu L_\nu]_{\text{peak}} = 3 \times 10^{-3} \dot{M}$$

$$\nu_{\text{peak}}(M) = 10^{15} \left(\frac{M_\odot}{M} \right)^{3/8} \text{ Hz}$$

Detection by SDSS

$$L_{\alpha} = \varepsilon_{\alpha} \dot{M}$$

Luminosity in band α

Fraction of \dot{M} in band α

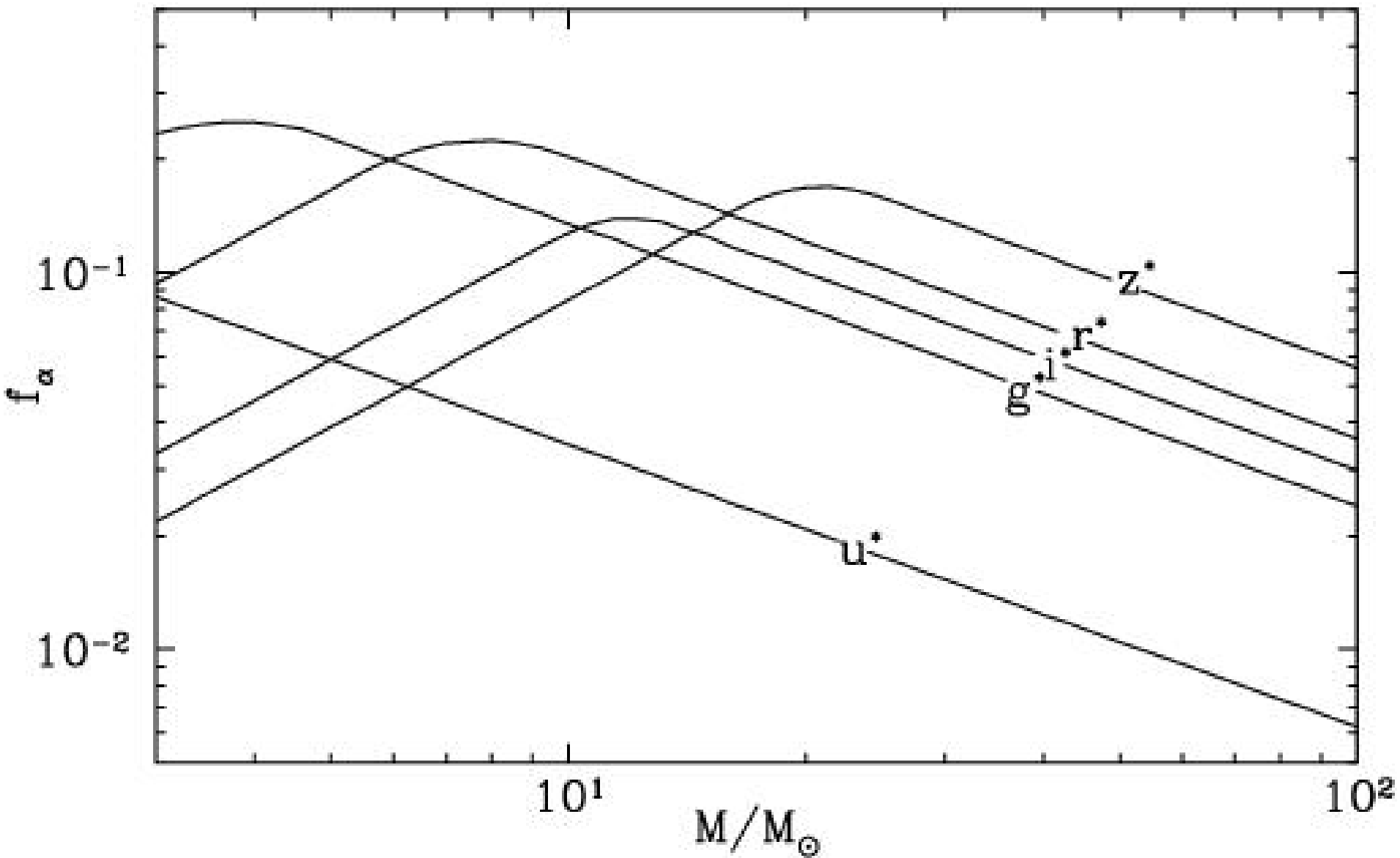
$$\varepsilon_{\alpha} = \varepsilon \times f_{\alpha}$$

Total efficiency $\approx 2 \times 10^{-3}$

Fraction of ε in band α

$$f_{\alpha} = \frac{\int_{\alpha} [\nu L_{\nu}] (d\nu/\nu)}{\int_0^{\infty} [\nu L_{\nu}] (d\nu/\nu)}$$

Detection by SDSS



Detection by SDSS

$$L_{\alpha} = \varepsilon_{\alpha} \dot{M}$$

$$\varepsilon_{\alpha} = \varepsilon \times f_{\alpha}$$

$$= 10^{-4} \left(\frac{\varepsilon}{2 \times 10^{-3}} \right) \left(\frac{f_{\alpha}}{5 \times 10^{-2}} \right)$$

- For ADAF models efficiency for each Sloan color $\sim 10^{-4}$
- Less for CDAF models

Detection by SDSS

properties of the ISM

- sound speed c_s
- density ρ

density and velocity distribution of holes

- fraction of local dark matter density f
- mass distribution of holes $dN/dM \propto (M/M_\odot)^{-(1+x)}$ $x \simeq 2$
- velocity distribution of holes $\sigma = 40 \text{ km s}^{-1}$

emission model

- IP, ADAF, CDAF, ...

observational parameters

- limiting magnitudes $m \leq 23$
- sky coverage 10^{-2} sr for Early Data Release

Detection by SDSS

number of detections in bandpass α

$$dN_{\alpha} = \left(\frac{\Omega_{\text{SDSS}}}{3} \right) d_{\alpha}^3(M, v) \Phi(M, v) dM dv$$

maximum distance can see a hole of mass M velocity v

$$F_{\alpha}^{\min} = \frac{L_{\alpha}(M, v)}{4\pi d_{\alpha}^2}$$

density of holes in the range $(M, M+dm)$, $(v, v+dv)$

$$\Phi(M, v) = \phi_v(v) \phi_M(M)$$

result is approximately

$$N_{\alpha} \simeq 10^6 f \left(\frac{\Omega_{\text{SDSS}}}{\pi} \right) \left(\frac{\varepsilon}{2 \times 10^{-3}} \right)^{3/2} \left(\frac{f_{\alpha}}{5 \times 10^{-2}} \right)^{3/2}$$

$$10^6 f \rightarrow 4.5 \times 10^4 f \text{ for Early Data Release}$$

Secret language of astronomy

magnitudes

larger magnitudes fainter
SDSS limiting magnitudes:

$$m_1 - m_2 = -2.5 \log \left(\frac{\text{flux}_1}{\text{flux}_2} \right)$$

$$u^* < 22.3 \quad g^* < 23.3$$

$$r^* < 23.1 \quad i^* < 22.3$$

$$z^* < 20.8$$

colors

$$u - g = -2.5 \log \left(\frac{\text{flux}_u}{\text{flux}_g} \right)$$

$$u - g$$

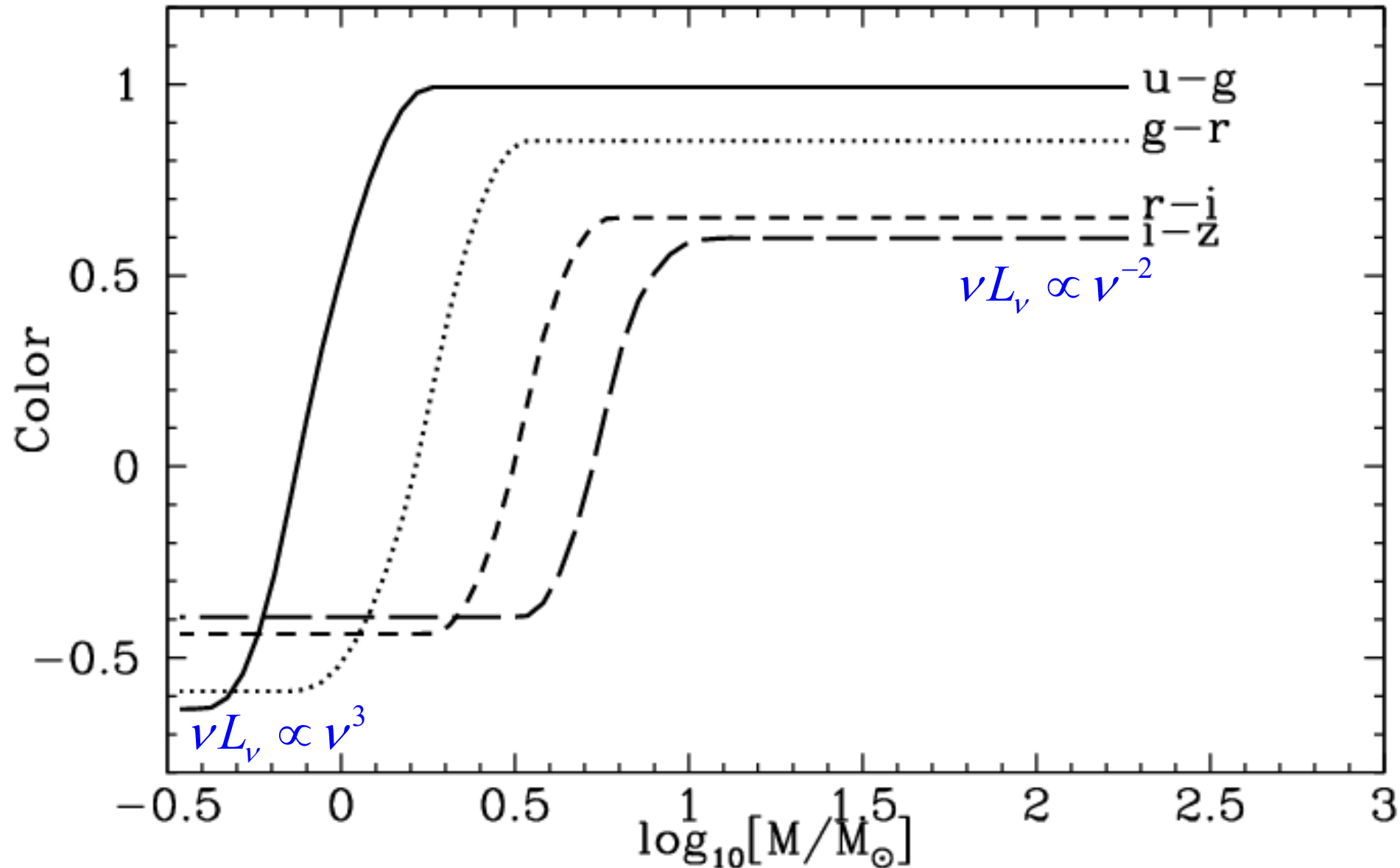
$$g - r$$

$$r - i$$

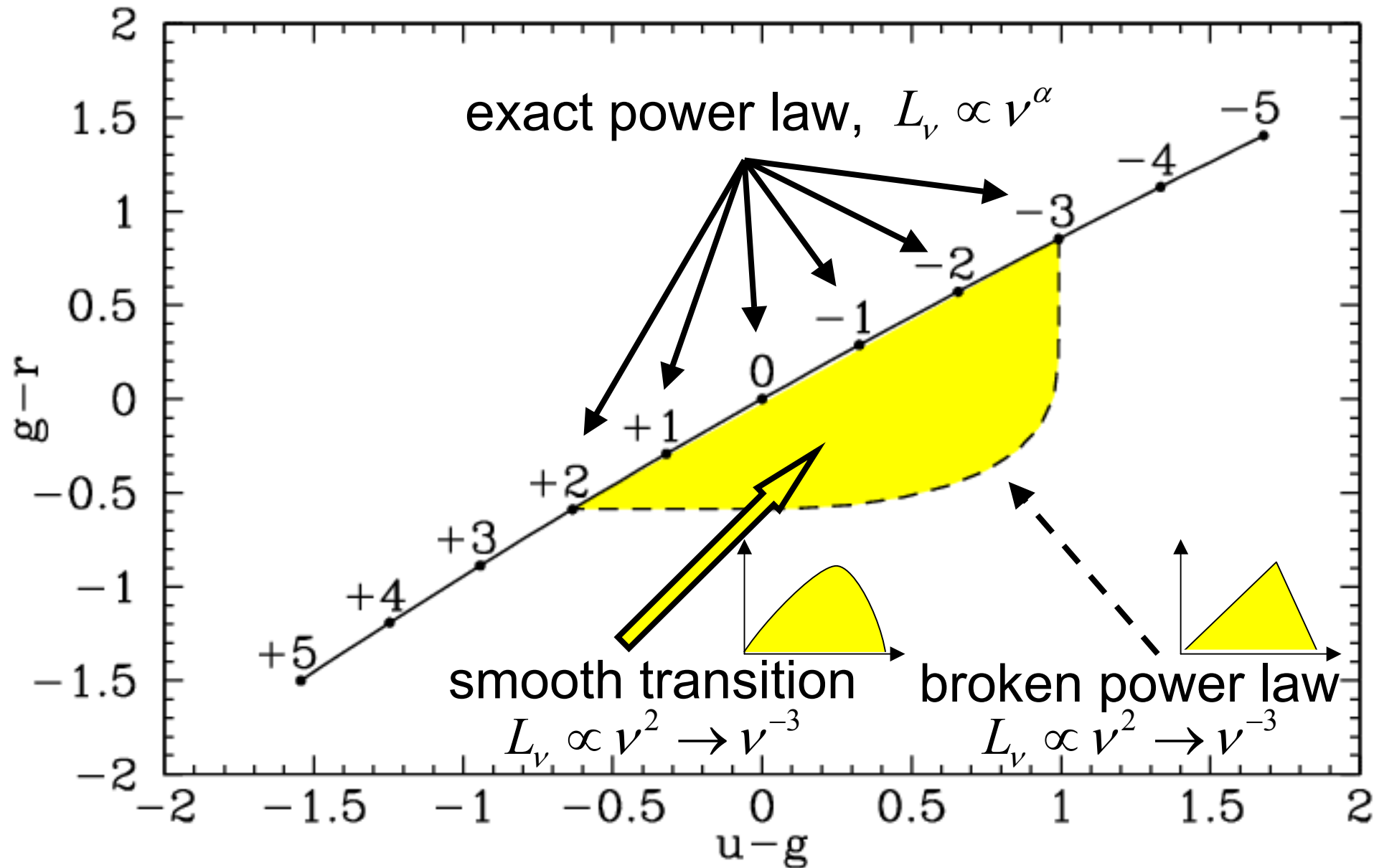
$$i - z$$

Colors for synchrotron sources

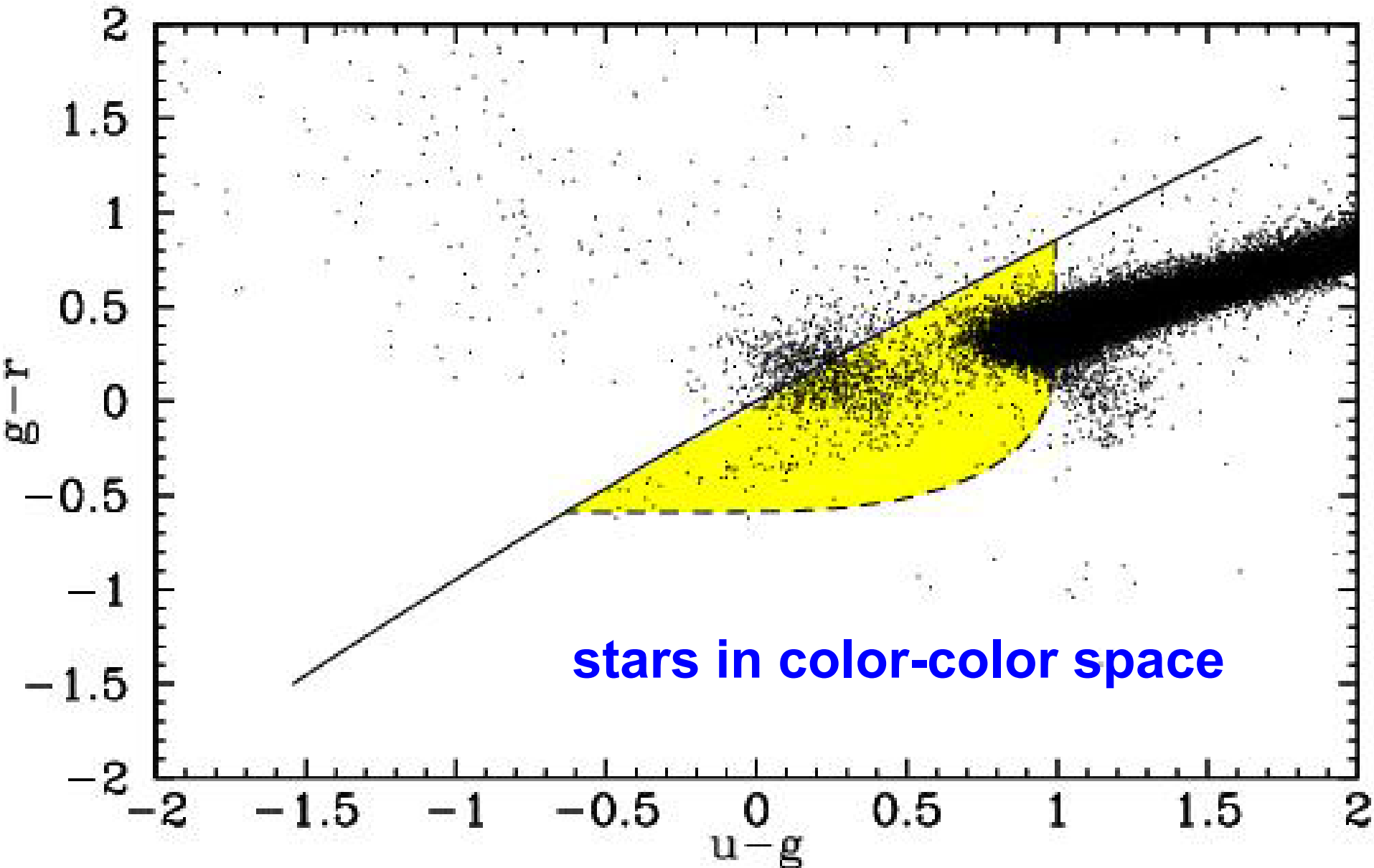
ADAF models



Color-color space



Color-color space



Color-color cut

SDSS 5 year mission:

- to seek out new objects in photometric survey
(π sr - 100 million objects in 5 colors)
- to explore the spectrum of galaxies & QSOs
(1 million)
- to boldly go where no survey has gone before

SDSS Early Data Release [Stoughton (2002)]:

- 462 square degrees
(3.7 million objects in 5 colors)
- 150,000 in color-color space of $u - g$, $g - r$, $r - i$, $i - z$

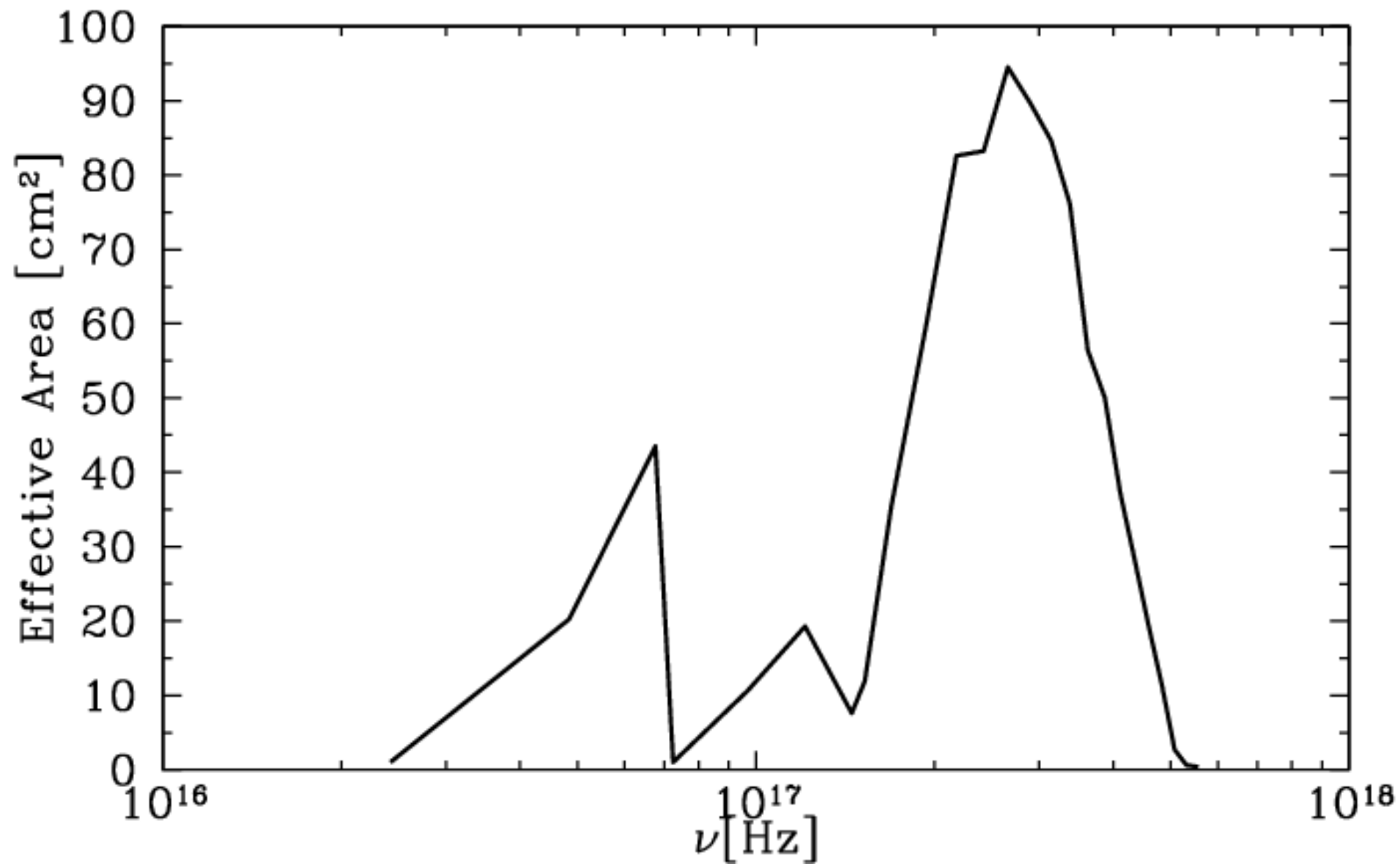
RASS **ROSAT All-Sky Survey**



ROSAT
Röntgen Satellite
X-Ray Observatory
Germany/US/UK
1990-1999

$0.1 \text{ keV} \leq E \leq 2.4 \text{ keV}$

ROSAT effective area

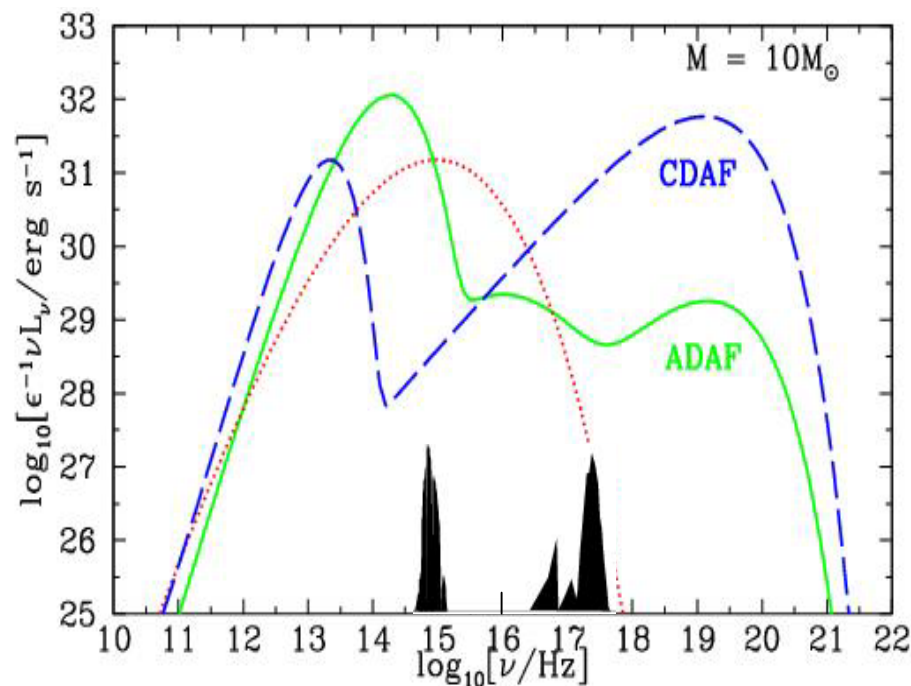


RASS count rate

$$\text{counts} = \left(\frac{1}{4\pi d^2} \right) \int_{\text{RASS}} A(\nu) [\nu L_\nu] (d\nu/\nu)$$

assuming flat L_ν

$$50 \frac{\text{counts}}{\text{k sec}} \left(\frac{\nu L_\nu}{10^{27} \text{ erg s}^{-1}} \right) \left(\frac{\text{pc}}{d} \right)^2$$



Color-color cut + RASS detection

SDSS = 150,000

SDSS + RASS = 47

47 is a manageable number

(can examine each individually)

7 targeted for spectroscopy by SDSS

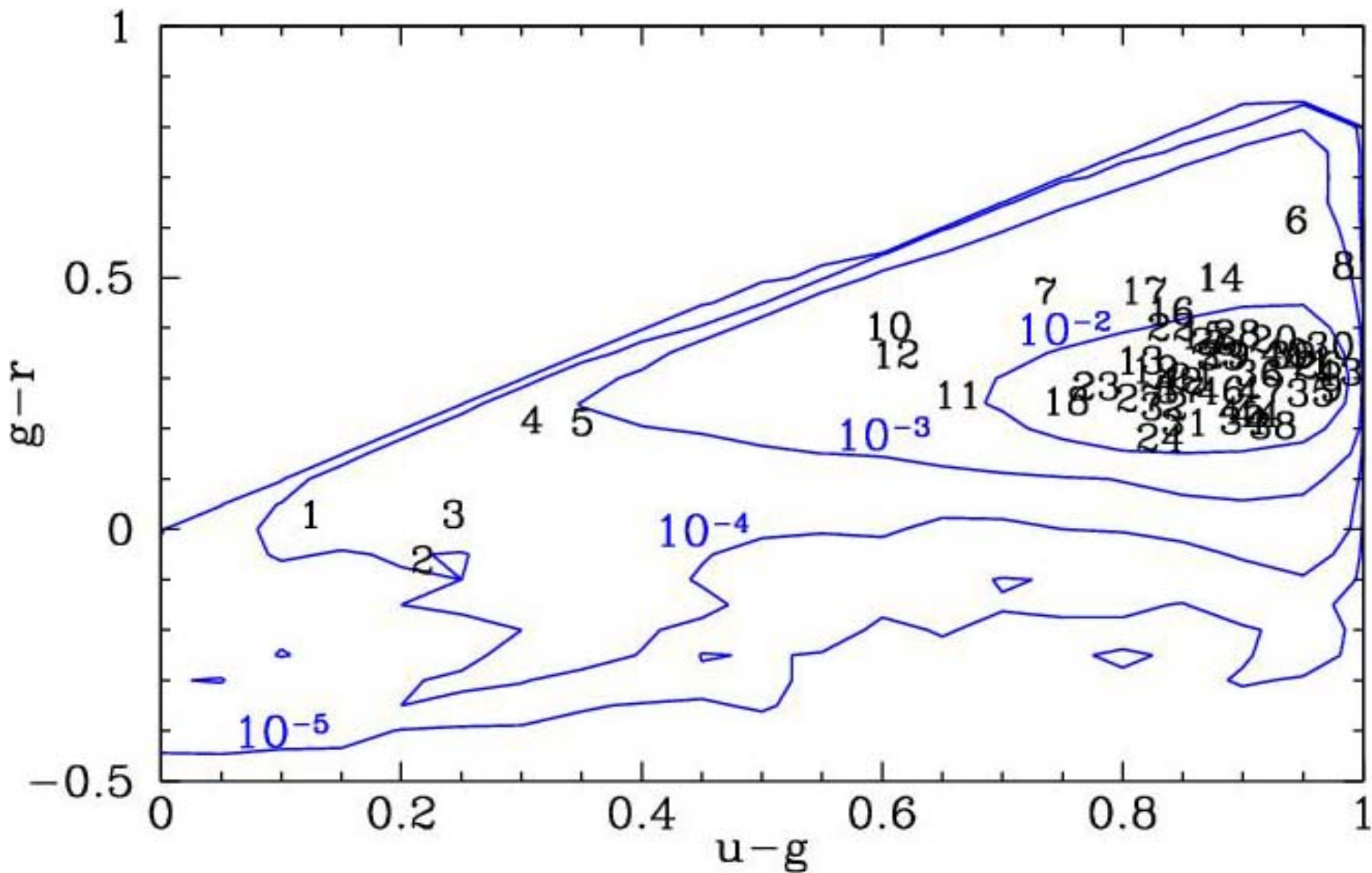
(5 stars + 2 QSOs)

Can define measure of how far from stellar locus in
4 color-color spaces

Find peak of stellar locus in each color-color space, and

$$D_i = \sqrt{\sum_{\text{colors}} \left(\text{color}_i - \text{color}_{\text{peak}} \right)^2}$$

Distribution in D



The Rocky Catalog

Rocky I

-
-
-
-
-
-

Rocky XLVII

The Rocky Catalog

Rocky I

#	RA		dec		u^*	g^*	r^*	i^*	z^*	RASS	D
1	17	20 25.2	55	40 06.7	20.64 ± 0.06	20.51 ± 0.02	20.51 ± 0.02	20.51 ± 0.02	20.51 ± 0.02	40 ± 7	0.88

Rocky I



Limits to f

Expect in the Early Data Release

$$N \simeq 4.5 \times 10^4 f \left(\frac{\varepsilon_\alpha}{10^{-4}} \right)$$

Have 40 possibilities, so

$$f \leq 10^{-4}$$

Assuming RASS would have detected all holes

Now what?

47–7 = 40 objects sorted by “D”

Follow-up observations

- spectroscopy

- variability

- proper motion

- x-ray flaring

With luck, evidence for “nearby,” “solar-mass” hole